Reversing Time: Decoherence, the Loschmidt Echo, and Quantum Computers

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An increasing number of scientists believe that the future of computers might depend more on the quantum rather than the classical laws of physics. The glimpses of the quantum computing power exhibited by theorists [1] motivated many experimental physicists into the quest to tame the quantum bits (*qubits*) in different settings.

However, the most intricate features of quantum mechanics (at the core of its promise for information processing) are, at the same time, the most fragile. Take for instance superposition: unlike its classical counterpart, a qubit can exist not only as a one or a zero, but also as both possibilities at once. This is essential for tasks such as factoring large numbers [1].

Unfortunately, in the "real world," arbitrary superposition states cannot last for long. The slightest interaction of the qubit to its surrounding environment will rapidly drive the quantum system to choose between one of its two classical options. In this way the quantum computer becomes, at best, an ordinary one. This process is known as *decoherence* [2], and it is the biggest roadblock for quantum information processing.

Our group has studied decoherence for a long time. We are now focusing on understanding those aspects of it that will help create and control a quantum computer. Recently [3] we were able to show that the rate of decoherence can be measured by an effect called Loschmidt echo. Named after the famous 19th century German physicist, the Loschmidt echo is an experimentally observable measure of the sensitivity of a quantum system's dynamics to small changes in its parameters. Classically, it is the probability that a billiard goes back to its original state if we could reverse all the velocities of the balls. The billiard's dynamics is so complex that even a small change, say the dust on the table changing its position, will have a profound effect on it (this is also known as the butterfly effect).

By relating decoherence to the Loschmidt echo we provided an experimental way to measure the rate at which decoherence affects the state of a quantum computer. This would mean a remarkable tool for experimentalists to quantify the degree of precision of the computer, or to characterize the physical system over which the computer is implemented, since Loschmidt echo experiments are already carried out in many of the settings that have been proposed for "quantum hardware." Furthermore, our results also mean a breakthrough in theoretical understanding of these processes, allowing the use of analytical tools developed to study decoherence in quantum information processing and in "quantum chaos."

Summing up, our work represents an important step in the understanding and characterization of decoherence. Its relevance goes beyond the fundamentals of physics to the applied efforts in quantum information, where *know thy enemy* is crucial in order to bring quantum computers to reality.

[1] M. Nielsen and I. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, 2000).
[2] W.H. Zurek, *Phys. Today* **44**, 36 (1991); W.H. Zurek, *Rev. Mod. Phys.* **75**, 715 (2003).
[3] F.M. Cucchietti, D.A.R. Dalvit, J.P. Paz, and W.H. Zurek, *Phys. Rev. Lett.* **91**, 210403 (2003).

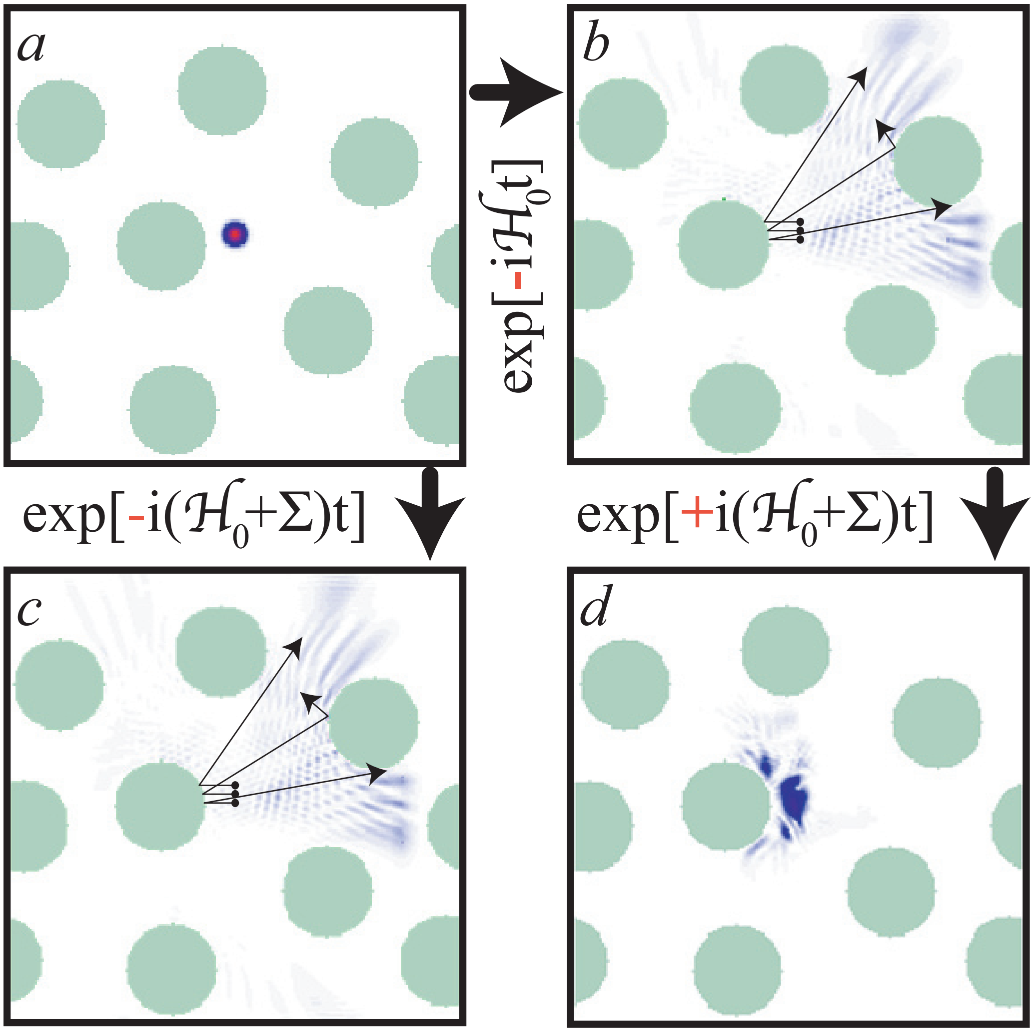

Figure 1—
***(a)** Gaussian wave-packet (blue) in a Lorentz gas, a box with hard wall spheres (green) where the particle cannot enter. The particle's velocity is pointing to the left.*

***(b)** The state of the particle after the collision with the sphere. Notice that its probability density has already started to spread.*

***(c)** An infinitesimal change in the spheres' roughness (represented by a Hermitian perturbation Σ) leads to approximately the same (indistinguishable to the eye) state of the particle. The black arrows in (b) and (c) are classical trajectories that start near the initial wave packet, showing that the roughness does not affect noticeably the classical motion of the system either.*

***(d)** Taking the state from (b), a Loschmidt echo is performed by changing the sign of time and adding the roughness Σ to the walls of the spheres. Notice that this time-reversed state is not the same as (a), showing the sensitivity of the system to the perturbation. The Loschmidt echo is the overlap between (a) and (d), and in this case is only below 10%.*